[a]A FLY-BY ROBOTIC TANK INSPECTION END EFFECTOR FOR WASTE STORAGE TANK

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ABSTRACT

A robotic end effector has been developed that is capable of performing fly-by, electromagnetic non-destructive evaluation (NDE) and visual inspection of the inside of the U.S. Department of Energy's waste storage tanks. Furthermore, the system is also capable of sizing defects through its unique NDE technique, Alternating Current Field Measurement (ACFM).[b] The NDE data is recorded and logged electronically and is tagged with the position data from the deploying manipulator, allowing a complete mapping of the tank walls and future return to defect sites.

I. INTRODUCTION

The waste that has resulted from the nuclear weapons research and manufacturing processes of the past fifty years has long been stored in large, underground tanks. These waste storage tanks can be as large as 40 ft. deep by 80 ft. in diameter, and capable of storing as much as one million gallons of waste. Many of these tanks are now believed to be in various stages of decay. Cracks, corrosion, or other structural damage could result in the release of highly toxic substances into the environment. To date, detailed knowledge of the structural integrity of these tanks has not been possible because of both the environment within the tanks, and the shortcomings of existing non-destructive evaluation (NDE) techniques. A new technique for inspecting and determining the structural integrity of the tank walls is the subject of this paper.

II. PROBLEM

Defects may be hidden or obscured by waste deposits and hence not visible to the human eye through a video monitor. Therefore, it is desirable to inspect via NDE as large an area of the tank wall as possible, in the shortest time possible. Additionally, it is important for both safety and planning reasons to understand the physical dimensions of any defect detected. Traditional methods of NDE are not viable for this type of large scale inspection.

III. SOLUTION

Oceaneering Space Systems (OSS) has resolved the problems relating to waste storage tank inspection by combining a unique electromagnetic inspection technique (Alternating Current Field Measurement, ACFM) with a compact vision and lighting subsystem,

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[a]Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under contract DE-AR21-93MC30363 with Oceaneering Space Systems, 16665 Space Center Blvd., Houston, Texas, 77058; fax: (713) 488-2027.

[b]UK Patents 92902693.8, 2286678A, 2224575; US Patents Pending.

and an integrated mechanical deployment subsystem. This Robotic Tank Inspection End Effector (RTIEE) is capable of several different inspection modes: (1) visual inspection, (2) detailed, quantified NDE, and (3) fly-by, which is a lower fidelity NDE performed while the manipulator is in motion and moving the RTIEE, at some standoff, across the surface of the tank wall. In each case, all inspection data can be recorded both to the computer's hard drive and to video tape. Importantly, the inspection data is linked with manipulator position data.

When the RTIEE is moved, or "flown", across the surface of the tank wall, it acquires both ACFM and visual inspection data. The ACFM data display scrolls across the screen in sync with the manipulator's motion and the real-time video. Manipulator position data is integrated into both the electromagnetic and video data streams, which allows later return to any points of interest; i.e., defect. Alternatively, the fly-by inspection can be halted at a detected defect, and the RTIEE can be landed over the defect for a detailed, quantitative inspection.

ACFM is uniquely capable of both detecting and sizing defects in any conducting material. In the RTIEE, ACFM sensor coils are mounted in a 96 coil array that is protected by a .010" stainless steel plate. This sensor array is driven across the RTIEE scanning frame for a detailed, quantified inspection of a 3"x 3" area. The data from this detailed scan is used to size any detected defect. Figure 1 shows the RTIEE sensor head deployed by a precision manipulator, performing a fly-by inspection on a 1/4" carbon steel plate. Note that the size and geometry of the array, the scanning mechanism, and the end effector itself are limited by the dimensions of available access ports and risers in the waste tanks.

Figure 1: RTIEE sensor flying over 1/4" welded plate.

IV. APPLICATIONS AND BENEFITS

- Electromagnetic inspection data is combined with visual data and manipulator position data to create a comprehensive and repeatable inspection record.

- Inspection can be conducted on the fly at speeds up to 1 in/sec in the prototype, and even faster in subsequent systems. Standoff distance is dependent on the size of the target defect.

- Determining the structural integrity of large portions of the waste storage tank walls is possible in a relatively short time, without exposing personnel to a hazardous environment or introducing secondary waste into the tank (1 in./sec. = 5 ft./min.; with a 6" swath = 2.5 ft^2/min.)

- The cylindrical, 10.5" diameter end effector geometry is designed to be deployed by the Light Duty Utility Arm (LDUA, or similar manipulator) through a 12" diameter access riser.

- ACFM can inspect any conducting material, through non-conducting layers if necessary.

- ACFM has significant advantages over traditional NDE technologies: unlike X-Ray, ACFM is a benign electromagnetic technique; unlike ultrasonics, ACFM does not produce secondary waste in the form of coupling fluid or gels; ACFM does not require direct electrical contact with the tank wall, and can both detect and size defects; ACFM is far less sensitive to standoff and mis-orientation than eddy current, and it can be used through most coatings and layers.

V. ALTERNATING CURRENT FIELD MEASUREMENT (ACFM)

ACFM is an electromagnetic NDE technique that has been specifically developed to overcome the shortcomings of eddy current techniques. ACFM combines the ability of the Alternating Current Potential Drop (ACPD) technique to size defects without prior calibration, with the ability of eddy current to work without electrical contact. This is achieved by inducing a uniform AC field in the target material and measuring the magnetic fields above the specimen. The uniform current flow can be modeled analytically, thus making the field response predictable and allowing characterization and sizing of defects. The use of the uniform field encourages the production of arrays of coils to cover large areas simultaneously even when relatively small defects are targeted.

VI. DESCRIPTION OF THE RTIEE

Figure 2 shows the full RTIEE prototype deployed by an OSS manipulator arm. A mockup waste tank wall can be seen to the left. Five subsystems make up the RTIEE: camera and lights, end effector body, ACFM sensor, software and operator interface, and data transfer system.

Figure 2: RTIEE deployed by OSS manipulator.

A. The Camera and Lights Subsystem

A CCD camera is mounted on the centerline of the end effector body. A motor driven lens is attached to the camera and a wide angle lens adaptor is attached to the lens. The lens adaptor increases the wide angle field of view to 56.6 degrees. This allows the operator to view the back of the scanning frame (useful when seeking contact with the tank wall), as well as view a distant object in telephoto mode without any of the scanning frame obstructing the view (useful for identifying potential inspection sites on the tank wall). Figure 3 shows the camera view when the end effector is pushed up against a wall; the status indicators for landing are shown in the upper right corner of the screen indicating nominal compression of all 3 struts.

The lighting system consists of two sets of lamps. The near set, mounted on either side of the camera, illuminate the rear of the scanner frame and the tank wall being inspected. The far set, mounted on the front face of the scanner frame, illuminate distant objects and are not used during stationary inspections. The remote iris, zoom, focus, and the intensity of all lamps are controlled by the operator from the operator interface screen. Local control logic circuitry mounted in the at-tank enclosure supports these functions, as well as the motor controller for the scanner.

Figure 3: Camera view when RTIEE is landed on a tank wall.

B. The End Effector Body Subsystem

The body consists of three main areas: the main body (cylindrical shell), the compression rods, and the scanner frame. The main body attaches to the Light Duty Utility Arm (LDUA) manipulator through the Tool Interface Plate (TIP). Three struts protrude from the opposite end of the main body and connect the scanner frame with the main body. These struts provide a compliant link to the main body, allowing the operator to land on the tank wall with up to 15 degree misalignment and within a 3 inch stroke range. The struts provide spring resistance after landing, and frictional damping of the LDUA against the tank wall. Because the atmosphere inside some tanks may create the danger of ignition, all components that could produce a spark are housed within a positive pressure containment vessel. This includes the camera, lights, scanner motor, array electronics, and induction coils.

The scanner frame carries the ACFM sensor array. The array is driven up and down by a cable drive system. This cable drive system is connected to a stepper motor that is geared down through a non-backdriveable worm gear arrangement. The cable system minimizes the locations in which tank debris could become lodged, is highly efficient, and eliminates the potential for mechanical jamming. The scanner frame carries the two near light assemblies. The spot reflector far lights are mounted on the bottom of the front face of the array frame.

The components of the end effector are designed for replacement in a glove box environment. Each component with limited radiation life is designed into a module that is replaceable with simple tools and hand operations. Besides the electrical systems, all items that do not have to be exposed to the environment of contaminants and potentially corrosive vapors are housed within the pressurized volumes in the end effector.

Figure 4 shows a close up of the end effector scanner frame. The far lights, excitation solenoids, and ACFM array are visible. The sensor array carriage can be seen in the lower half of the scanner frame.

Figure 4: RTIEE scanner frame.

C. The Software and Operator Interface Subsystem

The control and interface software was developed and written using Microsoft Visual C. The software architecture consists of specifically written modules combined in a robust and hierarchical manner. The operator controls the end effector using a customized graphical user interface (GUI). Figure 5 shows the operator interface screen. Mouse activated menus and control buttons surround the video window. All RTIEE lighting and camera functions are accessible from the on-screen control buttons. Data acquisition functions, data analysis tools, and system parameters are accessible through the pull down menus. The data analysis tools provide an interactive interface for detecting and sizing defects. ACFM scan data is represented as both a false color image and as a 2-D plot. The user selects areas of interest, and by specifying data points that represent defect magnetic signature features, the software analysis tools determine and report the size and depth of the defect.

All fly-by scan data and detailed quantitative NDE scan data is linked together in a historical database and used to generate a tank wall map. The tank wall map provides a high level map of the tank wall that shows which areas of the tank wall have been inspected, and the condition of the tank wall. It also provides an interface for the user to browse through the large quantity of inspection data.

Figure 5: RTIEE operator interface screen.

D. The ACFM Sensor Subsystem

The sensor system consists of two main components, the sensor array and the data acquisition electronics. The sensor array is made up of 64 Bz coils and 32 Bx coils arranged in three rows (one set of 32 larger Bz coils is used for coarse fly-by inspection in a 6" swath, and the other smaller Bz coils and the Bx coils are used for detailed stationary inspections). Behind each row of coils is a printed circuit board (pcb) populated with multiplexing and signal processing components. Each pcb is connected via a transition pcb to an umbilical. The umbilical connector and all the boards are mounted inside a carbon steel box located in the sensor array carriage. The umbilical connects the array to the data acquisition electronics. To protect the electronics and save cost, the data acquisition electronics are loaded outside of the tank environment in the At Tank Enclosure, which is connected to the control computer via a serial line.

The ACFM array inspects by inducing AC fields into the target material, in this case metal plate, and sensing disturbances in the field with sensor coils that are scanned over the plate. By referencing a theoretical model of the field and a data look-up table, the system can then size the defects. The prototype end effector includes three sets of solenoids that provide three orthogonal input fields (X, Y, and Z) and two orientations of sensor coil (Bx and Bz) to measure the different components of the magnetic field above the plate. The Z field solenoid is wound around the array carriage while the X and Y field solenoids are mounted along the sides of the scanning window.

The variation in the magnetic field caused by most defects is very small compared to the general field, so a normalization procedure is used to highlight the defect signal. Experimentation indicates that normalization of the whole scan area is the most effective method for stationary scans. To accomplish this, a complete scan of the 3" by 3" detail window on a known good plate is subtracted from all scans of similar material. This method has the additional advantage of removing all repeatable field variations caused by the presence of the structure of the end effector which surrounds the array. Normalization for fly-by scans consists of taking a single set of readings above a known good plate area, which is then automatically subtracted during the fly-by scan. A plate suitable for normalization would be made of the same grade of steel as the tank wall, and be the same thickness; it would also be of a large enough area to prevent the plate edges from disturbing the field produced by the end effector (currently this size is about 14"x14"). The normalization procedure need not be repeated once a suitable material has been scanned for archival as normalization data.

VII. TEST RESULTS

A. Fly-By Inspection

Fly-by inspection is the feature of the RTIEE that is used to inspect large areas for defects. In fly-by mode, the RTIEE collects NDE data while the robotic manipulator is in motion. Bz sensor coils are continuously interrogated using X and Y fields. This allows the RTIEE system to detect defects such as cracks in <u>any</u> orientation because even if a crack lies parallel to the direction of the current induced by one field, which would result in a very small field disturbance in that direction, it will still be detected in the presence of the other field. Scan data from both fields are displayed to the user in real time. Suspected defects can be flagged by the user for future inspection and analysis, or inspected in detail at the time of detection.

The resolution of the fly-by inspection is dependent upon velocity of the manipulator and the distance between the tank wall and the end effector sensors. The current RTIEE data acquisition system is capable of collecting two complete scans in one second. This results in the ability to detect a 1 inch crack at a 1 inch standoff while the robot manipulator is moving at 1 inch/sec. Work is currently underway to increase the throughput of the data acquisition system, which will allow higher manipulator velocities, up to 2 in/sec, for fly-by inspections.

B. Defect Detection and Analysis

As discussed previously, ACFM relies on the imposition of a uniform current field into the material to be inspected. Thus the disturbance of the field by a defect can be modeled analytically; the validity of the analytical model is dependent on skin depth. The smaller the defect that can be confidently characterized, the greater the accuracy of the assessment of the structural integrity of the tank wall. There are two aspects to this detection and sizing capability: the first is the ability of the operator to detect the presence of a defect in the magnetic field shown on the screen; the second is the accuracy of the algorithm that sizes the defect based on the amplitude and position of the disturbances in the various fields. The RTIEE design incorporates interactive detection and location algorithms to provide the operator with a real time graphical depiction of the condition of the tank wall. Analytical tools built into the RTIEE software are used to size a defect. These tools, or models, were created by determining the relationship between the disturbance of each field and the defect, and by running the theoretical model for all combinations of defect sizes against these relationships, and creating a look-up table of the results. This modeling greatly reduces the cost of developing an inspection tool by reducing the number of test plates required to calibrate the system to one.

The RTIEE detection and sizing algorithms use combinations of field and sensor data that depend on the material being inspected. Figure 6 shows the disturbance of the X-Bz field as it flows around and into a defect in a carbon steel plate. These experimental results closely match the response predicted by the analytical model, and illustrate the peak/trough pair seen by a Bz sensor. The Z-Bz disturbance is not modeled, but it is such a strong response that the RTIEE uses it to detect corrosion pits; sizing is still accomplished with the X-Bz and X-Bz combinations. In another carbon steel example, the X-Bz data is first examined by the operator for peak-trough pairs as shown at the top right of the screen in Figure 7. Having identified this, a peak can be located in the X-Bx data (top left of the screen) which will fall midway on a straight line between the X-Bz features. The locations of the X-Bz features are used to evaluate the length of the crack, while the amplitude of the X-Bx feature is used to calculate the feature depth.

Figure 6: Model of an X-Bz field in the presence of a defect.

Figure 7: Defect analysis screen showing X-Bz, X-Bx, and sizing data.

This robust approach to defect detection and sizing is only limited by the practicalities of field deployment. Essentially, small defects produce small field disturbances which decay close to the surface of the steel. Therefore if small defects need to be detected then the sensor head must scan, as a general rule, not more than one pit diameter or crack length away from the material surface. The type of steel in the tank wall can also affect results. Stainless steel represents a slightly different challenge than carbon steel because at the inspection field frequency used by the RTIEE (5KHz) the material has a significant skin depth (about .22" as opposed to .005" in carbon steel). This skin depth has the advantage of allowing the RTIEE to detect subsurface features, but reduces the surface sensitivity compared to mild steel with a very shallow skin depth. Results for the inspection of carbon steel by the RTIEE are reported in *Hughes and Gittleman, 1995*. The RTIEE can detect and size defects as small as .125"

VIII. OPERATIONS

The RTIEE is designed to operate in the extremely hazardous environment of the DOE's waste storage tanks. Ongoing modifications will give the system a $1x10^6$ rad life, are making it intrinsically explosion proof, and will provide protection from the corrosive environment inside the tanks (ph levels from 1-14). More importantly, the RTIEE is perhaps the only means by which very large portions of the surface area of these waste tanks can be inspected. At its current fly-by rate of 1 in./sec., the RTIEE can inspect 2.5 ft^2/min.; at the expected next generation rate of 2 in./sec., this could increase to 5 ft^2/min. A 40' deep by 80' diameter storage tank has a total surface area of approximately 10,000 ft^2. If one half of this area required inspection, the inspection time required by the next generation RTIEE could be as little as 17 hours, and the entire inspection record would be held in an integrated tank wall map data base.

IX. CONCLUSION

The RTIEE provides a single unit solution for visual and NDE tank inspections performed by robotic systems. It successfully incorporates a vision subsystem, lighting subsystem, fine positioning subsystem, ACFM NDE technology, and data analysis software into one integrated system. The RTIEE system has been successfully demonstrated in a series of manipulator tests using a laboratory waste tank wall mockup. During laboratory tests, operators used the RTIEE to visually identify an area of potential corrosion attack, perform a fly-by NDE inspection to detect a defect, and then perform a detailed, quantified electro magnetic inspection of that area. The inspection was accomplished with the compliant scanner frame, but not the ACFM coils, in contact with the tank wall. The current ACFM sensor and defect sizing software configuration has proved capable of detecting and sizing defects on stainless and carbon steel as small as 0.125". Furthermore, the technology developed as part of this effort is intrinsically reconfigurable, and could be modified to provide the same type of inspection service to a wide variety of applications.

ACKNOWLEDGMENTS

This work is sponsored by the DOE's Morgantown Energy Technology Center, and is conducted under the Environmental Management’s High-Level Waste Tank Remediation Focus Area. Oceaneering Space Systems would like to thank Cliff Carpenter of the METC for his technical management of this effort.

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